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Compressive Membrane Action in FRP NSM strengthened slabs

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Abstract

This paper outlines basalt and carbon fibre reinforced polymer (BFRP and CFRP) strengthening of laterally restrained concrete floor slabs. In-plane restraint has previously been shown to enhance slab capacity due to the development of internal compressive membrane action (CMA), which is generally neglected in codified strength assessments. By installing fibre reinforced polymers (FRPs) using the near surface mounted (NSM) technique, disturbance to the existing structure is minimised. The span-to-depth ratios of test slabs were 20 and 15. These were constructed with normal strength concrete ($\sim 40\text{N/mm}^2$) with 0.15% steel reinforcement. A tenth of one percent of FRP (either BFRP or CFRP) strengthening material was used to strengthen samples which were later compared with unstrengthened control samples. Investigations showed that FRP strengthening and CMA are generally separate, with limited overlap in terms of their contribution to capacity increase. Recommendations are then made for designers to better determine the capacity of FRP strengthened restrained slabs.

Keywords: Basalt, Carbon, FRP, BFRP, CFRP, Concrete, Arching.

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Introduction

It has been estimated that 87% of buildings which will be in existence in 2050 have already been built [1] and that 40% of global greenhouse gases are directly attributable to the built environment [2]. Hence, 'adaptive reuse' has become an established method for the construction industry to become more sustainable [3-5].

One potential application of adaptive reuse within structural engineering may be to strengthen existing floor slabs in order to increase their load capacity above that considered in their original design (e.g. changing from a domestic floor loading to light office floor loading, etc.). This can be achieved by using advanced strengthening materials such as fibre reinforced polymers (FRPs) [6-13] and detailed analysis methods to account for the additional flexural strength due to the addition of FRP strengthening along with in-plane arching behaviour which occurs due to the presence of in-plane restraint.

FRPs have relatively low weight and good corrosion resistance and their application using the near surface mounted (NSM) technique involves minimal intrusion within the structure and minimises exposure to fire, which is seen as particularly advantageous in situations involving the structural retrofit of multi-storey buildings [14].

The inclusion of restraint and internal arching effects are not typically considered by designers prior to initial construction. However, with retrospective structural analyses, they may lead to additional capacity being found.

Methods to quantify arching effects have been developed since the early part of the 20th century [15-21] and a range of approaches are now available. This research makes particular use of the arching theory developed at Queen's University Belfast [22-29]. However, arching theories have not been incorporated within modern European or American building design codes, although some specialist highway design codes do allow their use in bridge deck design.

While the individual strength enhancing characteristics of FRP strengthening and arching have been well known for many years, a review of the literature has shown that no research into the simultaneous combination of the two methods has been carried out. Hence, this research outlines the investigations carried out to determine the joint benefits of each approach.

Background

NSM, BFRP & CFRP

NSM strengthening of existing reinforced concrete structures can be traced back to strengthening bridge slabs with grouted steel reinforcement in 1949 [30] and, whilst strengthening using steel bars continues to be of interest [31][32], the use of FRPs has become more popular in recent years (e.g. [33]). Some bridges have also been built entirely or partially from FRP [34]. FRPs also offer faster construction, higher strengths, lower weights, and greater environmental durability compared with steel. However, their main perceived drawbacks are their higher initial costs and lower elastic moduli compared to steel. Basalt fibres are generated by melting basalt; which is one of the most common rocks found in the earth's crust; at 1300-1700°C and spinning the molten liquid [35] into thin fibres. However, their mechanical properties are dependent, to an extent, on the origin of the raw material and the exact production processes employed. Carbon fibres were first produced in 1958 [36] during carbon arc experimentation under high temperatures and pressures [37] and since their original discovery industrial methods to produce them have been refined.

FRP bars containing carbon or basalt fibres are then typically manufactured with either circular or rectangular cross sections using a pultrusion process to suspend the fibres within a polymer resin [38].

Compressive Membrane Action

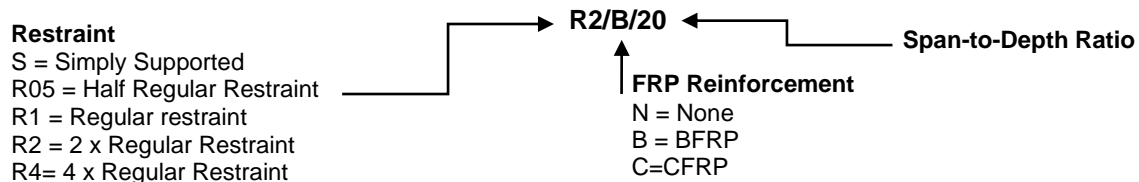
If the edges of a concrete slab are restrained against lateral movement, internal arching develops as the slab deflects [39]. This arching behaviour is known as compressive membrane action (CMA) and has been shown to enhance the flexural and shear capacity of reinforced concrete slabs [38][40].

The Queen's University Belfast (QUB) arching theory was initially developed by Rankin [41], based upon earlier investigations by Ockleston [16][17], McDowell et al. [18] and Park [19-21]. This 'QUB Arching' theory was later published by Rankin and Long [42]. Taylor [40] subsequently refined the concrete compressive stress block parameters therein for application of the QUB arching theory to high strength concrete. In the Rankin and Long [39] approach, the degree of lateral restraint was dealt with using a three-hinged arch analogy, whereby the behaviour of an arch with elastic spring restraints was equated to the behaviour of a longer rigidly restrained arch.

The prediction of ultimate capacity was based on the deformation theory of McDowell et al. [18]. The effects of arching and bending were considered separately although, in reality, compression in concrete was due to the action of both arching and bending. This arching analysis was further developed by Taylor et al. [43][44] for bridge deck slabs with high strength concrete ($>70\text{N/mm}^2$).

Experimental Investigations

Seventeen test slabs were cast with levels of restraint relative to that found in a typical floor slab within a multi-storey framed building, i.e. 'half', 'regular', '2x regular' and '4x regular'. Span-to-depth ratios of 20 and 15 were chosen which resulted in test slab depths of 83mm and 111mm respectively. These were constructed from concrete with a target compressive cube strength of 40N/mm^2 and an elastic modulus of 26753N/mm^2 . Steel reinforcement and FRP properties were established from tensile tests [45] and are shown in Table 1. Where FRP strengthening was employed, using the NSM installation technique, 0.10% relative to slab area was used. For ease of identification, test slabs were coded using the following format:



Test slabs were simply supported on 75mm wide support plates and Linear Variable Differential Transformers (LVDTs) were located as shown in Figure 1 to measure end face and midspan movements. Strain gauges bonded to restraint beam reinforcement allowed restraint forces to be recorded throughout loading. Compressive and tensile stress profiles within concrete in restraint beams were determined using Thorenfeldt et al. [46] and Feenstra et al. [47] constitutive relationships to allow the determination of restraint forces. In-plane restraint stiffness values were subsequently determined. The capacities of each test slab were established from testing under monotonic loading using a 600kN hydraulic actuator and compared with European [48][49] and American [50][51] code estimates

alongside QUB Arching theory predictions. The results of these findings are presented in Figure 2.

Table 1: Steel Reinforcement and FRP Properties

Bar Type	Area (mm ²)	Upper Yield, R_{eH} (N/mm ²)	Lower Yield, R_{eL} (N/mm ²)	Yield Strength, f_{yk} (N/mm ²)	Rupture Strength (N/mm ²)	Elastic modulus, E_s (N/mm ²)
6mm Steel	28.3	499	483	499	-	205.5×10^3
32mm Steel	804	-	-	485	-	200×10^3
CFRP	19.65	-	-	-	990	77452
BFRP	13.34	-	-	-	1138	35025

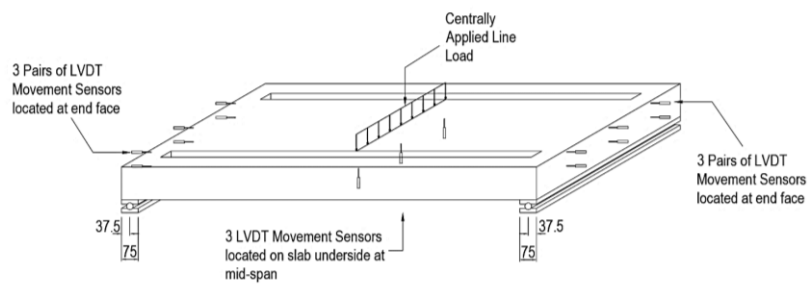


Figure 1: Typical test slab setup

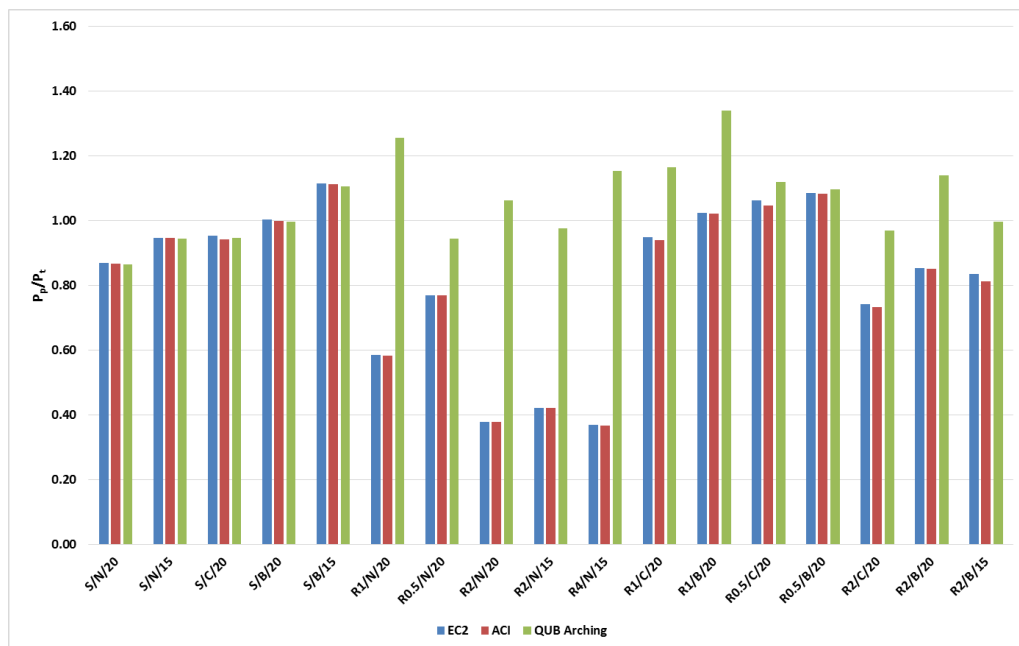


Figure 2: Comparison of P_p/P_t Ratios from Current European & American Design Codes Alongside QUB Arching Theory

Conclusions

The research showed that significant additional capacity can be either 'found' within existing reinforced concrete floor slabs by accounting for the restraining effects of their adjacent parallel floor beams or, if necessary, can be further increased by the addition of low proportions; approximately 0.10%, of CFRP or BFRP strengthening applied using the near surface mounted installation technique. Hence, this alone has offers the possibility of increasing existing slab capacities leading to greater sustainability within the construction industry. Investigations also showed that European and American code estimates were generally similar in all cases and that these were reasonable in instances where test slabs were simply supported. However, where in-plane restraint was present, code estimates were significantly lower than those obtained using the QUB Arching Theory. Therefore, as a first step, it is recommended that in-plane restraining effects should be accounted for by design engineers seeking to 'find' additional load capacity in existing reinforced concrete floor slabs.

As American and European code estimates of slab capacities were much closer to those achieved using the QUB Arching theory in cases where FRP strengthening and in-plane restraint were present, it can be concluded that there is an 'overlap' between the relative benefits of FRP strengthening and arching behaviour. These investigations therefore suggest that, in such instances, FRP strengthening alone should only be considered in cases where in-plane restraining effects are 'half regular' or 'regular' and that arching effects should only be considered, in addition to FRP strengthening, where in-plane restraining effects are '2x regular'. It can also be concluded that, with an average $P_p/P_t = 1.06$ for the series of test slabs under investigation, the QUB Arching theory is a reasonably accurate means of estimating slab capacity where FRP strengthening and in-plane restraint are present. However, due to its lack of conservatism, a safety factor on the application of the QUB Arching theory within design practice is recommended.

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